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Spinal Rotation During Running

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Spinal Rotation During Running

(An analysis of the correlation between spinal rotation and impact forces)

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A Major Qualifying Project Report
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Submitted to:
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Abstract

Many hypotheses have been made correlating ground reaction forces and spinal rotation during running, but not much has been done to test these theories. The purpose of our analysis was to determine, through testing, the correlations between the three-dimensional ground reaction forces and spinal rotation during running. We selected a test group of 20 males with competitive running experience. Due to the increasing popularity of barefoot running and the drastic variable that shoes add, subjects ran trials barefoot and with shoes. Data was simultaneously collected during trials via a force plate, mechanical spinal rotation device, and a high speed video camera. The force plate provided a center of pressure and ground reaction forces and moments in the x, y, and z directions; the rotation device provided the maximum angle of spinal rotation; the video allowed us to calculate the speed of the runner and the acceleration, velocity, and angular acceleration and velocity of each leg segment. From our analysis, we were able to draw correlations between the spinal rotation, speed of the runner, ground reaction forces, and the effects of running barefoot v. shoes.

Acknowledgements

We would like to thank all those individuals who helped us in our research and design work for this Major Qualifying Project.

Krystyna Gielo-Perczak, WPI Senior Lab Manager & Instructor
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Test Subjects

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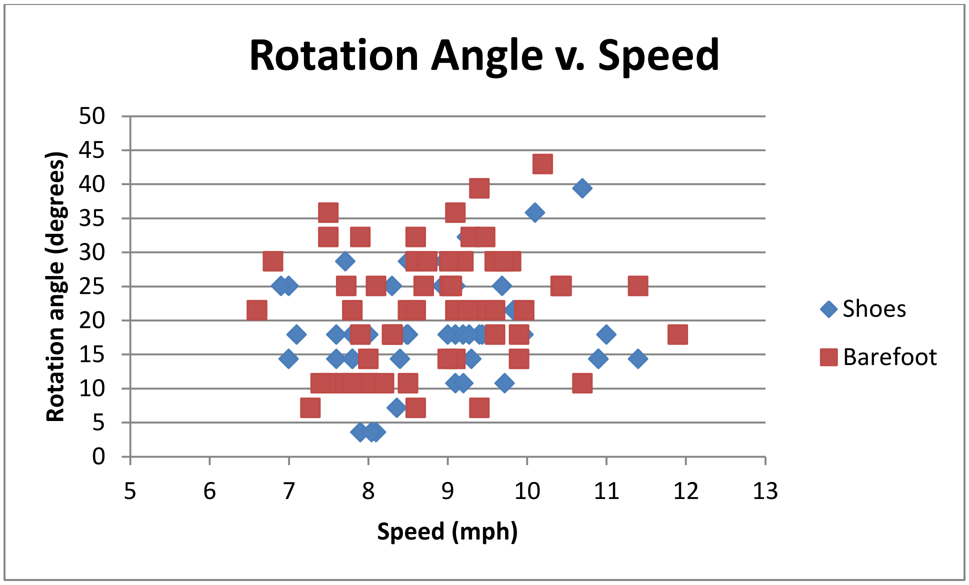
Executive Summary

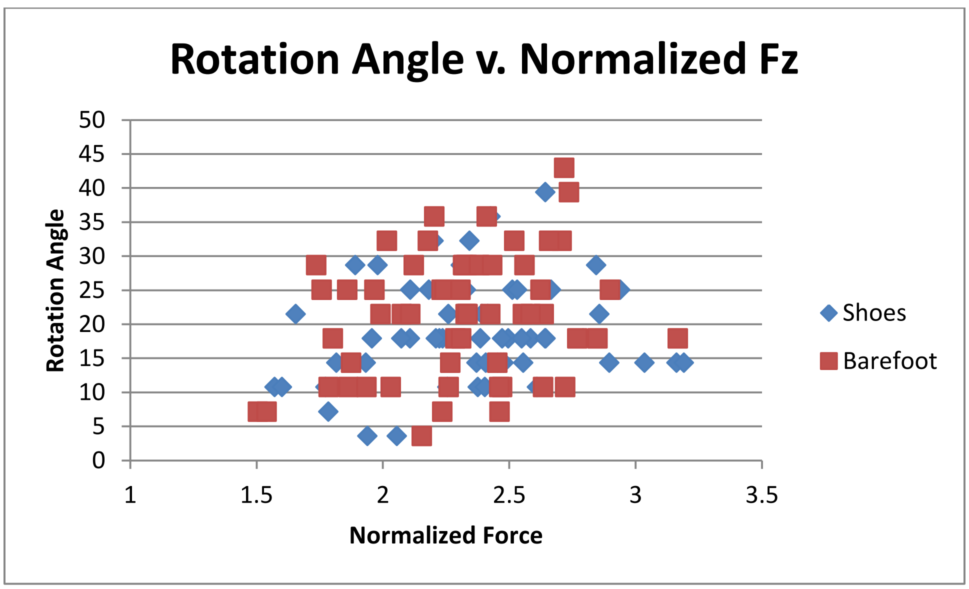
The focus of this project involved testing the hypothesis that spinal rotation affects the occurrence of injuries incurred during running. In order to test for injuries the project team examined impact forces in the foot, speeds of the runner, as well as leg accelerations in 3 sections. The impact forces were tested in three dimensions with an AccuSway force plate. The force plate was chosen because it was accessible and is capable of recording not only forces; but impulse, stance time, center of pressure, and more. Video analysis was also conducted in order to find accelerations of the leg and running speeds. A high frame-rate camera (120 f/sec) was used in conjunction with video editing software to calculate both the accelerations and speeds. Maximum spinal rotation was measured using a mechanical device designed by the group. The group also decided to test barefoot vs. shod to rule out any way different shoes affects natural gait, and because of the recent increased popularity of barefoot running.

The group tested 20 male runners with previous running experience. Each runner recorded 3 trials in their trainers(shod), and 3 trials barefoot. For each trial the runner would run approximately 50 meters through a force plate, allowing time to speed up and slow down gradually. The runner was asked to land each time on their right foot, and to maintain a running speed around 6-8 miles per hour. During each test force plate, video analysis, and spinal rotation was measured simultaneously.

After all of the testing data was compiled and analyzed, the project team's conclusions included the following:



The group found that for both barefoot and shod, there is no statistical relationship between spinal rotation and speed of the runner.



There also proved to be no statistical relationship between spinal rotation and vertical impact forces. Interestingly, after a pairs comparison was done it was found that 73% of test subjects exhibited higher spinal rotation while barefoot. From this, the group concluded that there was no relationship between spinal rotation and impact forces while running.

Introduction

Throughout the biomechanics field, there has been ongoing research of methods for reducing the impact forces in the lower limb during the gait cycle. One hypothesis for this has been increasing/decreasing the angle of spinal rotation, yet little research has been conducted to test this theory.

Over the course of the project, our team developed a method for testing the ground impact forces and angle of spinal rotation during running. An AccuSway^{Plus} force plate, mechanical spinal rotation device, and high speed camera were used in combination to gather the forces, angle, and speed/acceleration data needed for analysis. We selected a test group of 20 males, ranging in age from 18 to 22, all with prior experience in competitive running. Prior to testing, each test subject was warned of the potential risks of this testing and then was required to sign a waiver of liability.

A two phase testing procedure was developed: 1) measurement of the ground impact forces and maximum angle of spinal rotation in the upper back, both recorded at a controlled running pace; and 2) video analysis to determining the speed and acceleration of the test subject and their limbs.

The resulting test data was used to determine how the forces, speeds, and rotation angles were interrelated. Our results have to potential to be used by biomechanics and medical professionals to determine ways to reduce running induced injuries.

Background

History of Gait Analysis

Since the beginning of mankind, humans have been intrigued by the manner in which we walk. The earliest recorded comments on gait are attributed to Aristotle, who generated his own theories on the movement of animals and humans in 300 B.C. It was not, however, until the 17th century, with Giovanni Borelli's analysis that the field of gait analysis began to further develop. (Baker, 2007; Cavanagh, 1990)

Borelli, student of Galileo, is known for conducting the first scientific experiments in gait analysis. Through his pioneering research, Borelli concluded that medio-lateral rotation occurs in the head while walking. He conducted the experiment by walking directly from one set pole towards another; his conclusion was made because one pole appeared to be moving side-to-side. Also, due to Borelli's studies on mechanics in the human body; he deduced that more force appears in muscles than is externally applied, and also determined the location of the center of mass of the human body. Many of his observations and experiments were published in "De Motu Animalium," which serves as a bridge between the classical views of movement and modern science. (Baker, 2007; Cavanagh, 1990)

In 1836, Wilhelm and Eduard Weber released a long and detailed publication discussing numerous aspects of gait in walking and running. They were well-known mathematicians who conducted a number of scientific experiments on gait using simple methods. They conducted their experiments "using only a stop watch, measuring tape and a telescope," and were able to draw reliable conclusions about the phases of gait. Most importantly, they measured the differences between walking and running, as well as how speed affected stride length. They drew critical, reliable, and measured conclusions about gait. (Baker, 2007; Cavanagh, 1990)

Jules Marey and his student Carlet were the first to relate Newton's laws of physics to the behavior of human motion. Marey also was the first person to record a sphygmograph or cardiogram. Carlet took these instrumentation based studies one step further. By putting three force transducers inside the sole of a shoe, he was able to measure the ground reaction forces and record the first "double bump" GRF graph. This pair of individuals was the first to use true instrumentation in gait analysis. Eadweard Muybridge, while working on his analysis of "Horses in Motion", was the first to use photography in the field of gait analysis. He took a series of pictures perpendicular to a horse running in a straight line. Because he took multiple pictures for each gait cycle, he was better able to observe minute details. The use of photography helped to improve the ability to observe moving gait and analyze separate time intervals during gait. (Baker, 2007; Cavanagh, 1990)

Around the turn of the 19th century, Braun and Fischer became the first scientists to conduct a 3-dimensional analysis of forces incurred in gait. Their experiments involved developing an electrical suit for the subjects to wear. The suit emitted flashes from the inertial points of the body; Braun and Fischer recorded a continuous exposure of the flashes to document all of the movements sequentially. They then performed a force analysis on the recordings. Soon after this, A.V. Hill developed the first one-dimensional force plate, and then Herbert Elftman developed his own 3-dimensional force plate. These developments simplified the process of analyzing reaction forces.

Currently, there are numerous commercially available force plates for gait analysis, including three-dimensional force plates which simultaneously measure the three force components and the three moment components along the given x, y, and z axes. Recent developments in methods and instruments in the field of gait analysis involve the use of goniometers, accelerometers, video analysis, and computers. (Baker, 2007; Bertec, 2009; Cavanagh, 1990)

Gait Cycle

In humans, walking utilizes a reciprocal gait that alternates between the two legs; the two reciprocating gait cycles are called stance and swing. Stance describes the foot being planted, while swing describes the motion of the other foot suspended in air. The gait cycle is comprised of 8 separate phases, named to accurately describe each aspect of the human gait cycle. In order, the phases are: initial contact, loading response, midstance, terminal stance, preswing, initial swing, midswing, and terminal swing. For our analysis, the priority was to focus on initial contact/loading response and terminal stance. (Perry, 1992)

The initial contact phase of walking and running occurs when the foot first comes into contact with the ground. At this time the foot makes a 90˚ angle (+/- 3˚), with the normal force coming from the ground and the impact reaction forces throughout the leg. Loading response, which immediately follows initial contact, is when the limb bears the total body weight and the body tries to dampen the impact. During loading response, the ankle flexes to absorb initial impact, placing it under a significant amount of plantar stress. Knee flexion also occurs in response to ground reaction forces, in addition to an impact-induced internal tibia rotation. (Baker, 2007; Ball State University, 2010)

Terminal stance occurs when the continued forward momentum in the upper body causes the heel to rise and a forward motion occurs. Toe-off takes place during terminal stance, where the toe pushes off the ground and the ankle plantar flexes up to 20˚, generating most of the torque needed for propulsion. During terminal stance the foot and ankle are put under a large amount of stress (see Figure 1), resulting in the occurrence of the largest ground reaction forces of the entire gait cycle. (Ball State University, 2010; Perry, 1992)

Figure 1 shows a typical graph of vertical reaction forces related to time while running. The impact peak (P1) represents the initial contact. The propulsion peak (P2) represents terminal stance. This graph shows that the greatest amount of force is generated at toe-off, when these maximum vertical forces are approximately 2-3 times the body weight. (Ball State University, 2010)

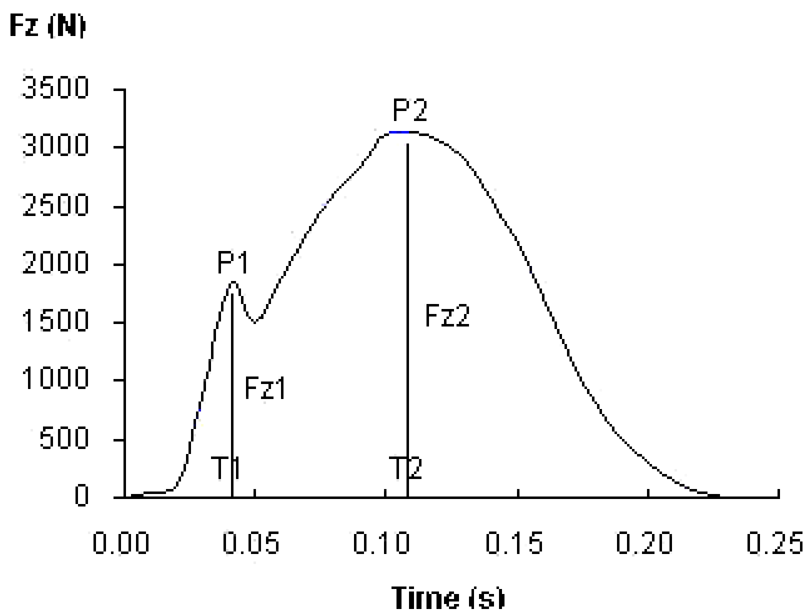


FIGURE 1: VERTICLE REACTION FORCES V. TIME, WHILE RUNNING (BALL STATE UNIVERSITY, 2010)

Normal Gait and Abnormal Gait

Gait analysis is a complex task because there is no standard model for normal gait. Every individual has a unique normal gait which is a combination of their stride length, foot pressure, and upper body behavior; this combination is determined by the individual’s walking/running form. Abnormal gait for an individual is a variation from that individual's normal gait. (Perry, 1992)

Abnormal gait is one of the most widely known causes of overuse injuries. Analysis of the gait cycle indicates that certain details of an abnormal gait show related effects, including injury, on the body.

The degree of plantar flexion in the ankle is an important factor in normal versus abnormal gait. Excessive plantar flexion during loading response results in a loss of progression, a shortened stride, and reduced stability while too insufficient plantar flexion places more demand on the knees and quads. (Perry, 1992)

Abnormal ankle movement is commonly described with the terms pronation and supination. The movements occur along the subtalar joint, and are on average a 4-6˚ rotation in either direction. (Figure 2)

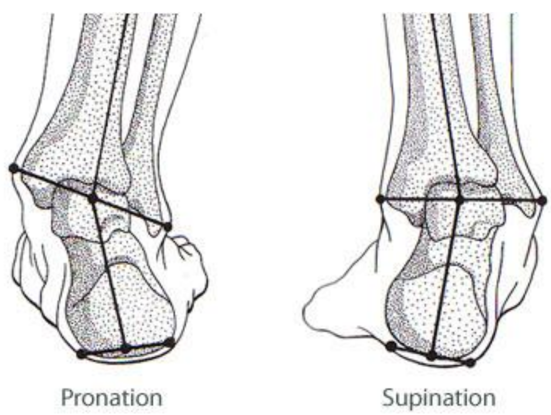


FIGURE 2: PRONATION V. SUPINATION

(KOLOWSKI, 2010)

Pronation is when the ankle rolls inward; it occurs naturally when the heel first strikes the ground at impact. The degree of dorsiflexion in the ankle and internal rotation of the tibia both will directly correlate to the degree of pronation at this instant. The average amount of dorsiflexion is about 10˚ and the average internal tibia rotation is about 7˚. Supination is when the ankle rolls outwards; it occurs naturally when the foot pushes off of the ground. Similarly to pronation, the degree of supination will directly correlate to the amount of plantar-flexion and external tibia rotation during toe-off. At this time, the average amount of plantar-flexion is 20˚, and the tibia rotation will restore itself to the original position by turning back 7˚. Both pronation and supination can predict effects on the rest of the body. For example, high arches commonly are associated with supination, while pronators are likely to have flat feet. The consequences of pronation and supination are indicated in Table 1 below.

TABLE 1: EFFECTS OF PRONATION AND SUPINATION UP THE KINETIC CHAIN (DUGAN AND BHAT, 2005)

	Pronation			Supination		
	Sagittal	Frontal	Transverse	Sagittal	Frontal	Transverse
Lumbosacral	Extension	Lat flexion same side	Protraction	Extension	Lat flexion opp side	Retraction
Pelvis	Anterior rotation	Translation and elevation, same side	Forward rot same side	Anterior rotation	Translation opp side; depression same side	Rear rot same side
Hip	Flexion	Adduction	Internal rotation	Extension	Abduction	External rotation
Knee	Flexion	Abduction	Internal rotation	Extension	Adduction	External rotation
Ankle	PF-DF		Internal rotation	DF-PF		External rotation
STJ	PF	Eversion	Adduction	DF	Inversion	Abduction
MTJ	DF	Inversion	Abduction	PF	Eversion	Adduction

Abbreviations: DF, dorsiflexion; Lat, lateral; MTJ, midtalar joint; Opp, opposite; PF, plantarflexion; rot, rotation; STJ, subtalar joint.

Foot Pressure Distribution

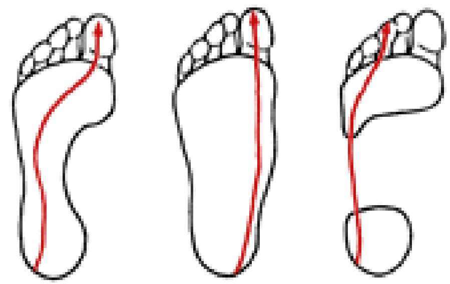
Variations in foot pressure distributions can directly correlate to a number of overuse injuries. Such injuries include stress fractures, shin splints, tendonitis, and compartment syndrome. (Wilder & Sethi, 2004)

The foot serves as the only connection between the moving (human) body and the surface of the ground. Thus, any deviation in balance, terrain, amount of propulsion, or natural gait certainly will make a difference in the specific pattern in which the foot reacts with the ground.

Center of pressure distributions are the path of instantaneous centers of pressure caused by the foot as it progresses through the stance phase. Center of pressure distributions have been difficult to quantify numerically; however, the differences in their patterns display foot strike placement, forward and lateral movement paths, the projection of the center of mass, and tendency to injury,. A typical pressure distribution will move medially from the outside of the heel until the end of toe-off when it will shift slightly back to the outside of the foot.

Analysis of runners indicates that one of the significant differences between runners is determined by where each runner's foot strikes the ground. Runners are classified as either a rearfoot, midfoot, or forefoot striker; nearly 99% of elite endurance runners have a rearfoot or midfoot strike pattern. Between the rearfoot and midfoot strikers there is no evidence that one of the patterns is more efficient or more likely to produce injury. Examples of typical center of pressure graphs for rearfoot and midfoot strikers are shown in the figure below. The rearfoot striker lands on the back-right portion of the foot, rolls in towards the center, and pushes slightly back toward the right at toe-off. The midfoot striker follows the same end-path but lands on the center-right portion of the foot.

For pronators and supinators, center of pressure graphs can show great differences. A natural pronator will have a center of pressure line migrating along the inside of the foot while a supinator's distribution will be along the outside of the foot. Typical center of pressures for a normal runner, pronator, and supinator are shown in Figure 4, below.



Neutral runner Pronator Supinator

FIGURE 3: PATHS OF CENTER OF PRESSURE

(BERNT ERRSON, 2002)

One method, utilized by orthopedic researchers, has been valuable in quantifying center of pressure. To evaluate forward and lateral movements and relate it to pronation/supination, the anteroposterior index (API) and the center of the pressure excursion index (CPEI) are calculated. The API evaluates forward movement, and can show how much of the foot contacts the ground during stance. It is calculated by dividing the length of the pressure line (b), by the length of the subject's foot (a), API = (b/a) x100. The CPEI is used to evaluate medio-lateral movement; it is a good indication of pronation or supination. It can be calculated by dividing the lateral distance between the farthest point and a constructed centerline (c), by the maximum width of the foot (d), CPEI = c/d. The CPEI could be a way of quantifying the degree of pronation in subjects.

Muscle Activation during Gait

As the following text and figures show, different phases of the gait cycle result in the activation of specific muscles.

At initial contact, the activated muscles include the quadriceps, glutes, hip extensors, and tibialis anterior. (Figure 2) These muscles counteract the moment forces which are generated at impact in the ankle and hip. (Auckland Bioengineering Institute, 2009; Perry, 1992)

FIGURE 4: MUSCLES ACTIVE AT INITIAL CONTACT

(AUCKLAND BIOENGINEERING INSTITUTE, 2009)

During terminal stance, the active muscles are the ankle plantar flexors. (Figure 5) The largest moment force and vertical ground reaction force occur at this point in the gait cycle. (Auckland Bioengineering Institute, 2009; Perry, 1992)

FIGURE 5: MUSCLES ACTIVE IN TERMINAL STANCE

(AUCKLAND BIOENGINEERING INSTITUTE, 2009)

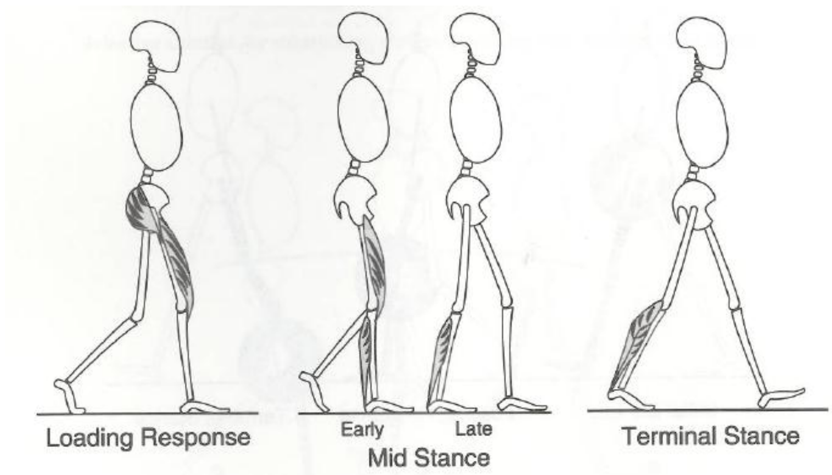


FIGURE 6: ACTIVE MUSCLE GROUPS IN GAIT CYCLE

(PERRY, 1992)

Comparing Runners of Different Size and Speed

The body weight and speed of runners affect the forces measured in the foot. Because forces measured in the foot vary depending on the body weight of the runner, statistical analyses should account for differences in body weight when comparing different test subjects. (Keller et al., 1996)

The study conducted by Keller, et al. indicates that the force data from a test subject can be normalized by converting to a percentage of the subject's body weight (%BW). (The study tested athletes who were "within the range of normal weight for their height.") (Keller, et al., 1996)

Another study, conducted by Munro, Miller, and Fuglevand showed that as running speed increased, ground reaction forces also increased in a linear fashion for speeds 3 to 5 meters/second (or 8.9 to 5.4 minutes/mile). Based on the results of Munro et al showing that reaction forces are related linearly to speed ($p<.001$), it is possible to gather data from runners at different speeds and create a linear regression model suitable to normalize for velocity. Research shows that the foot strikes the ground differently as speed changes: at speeds of 6 m/s and up, most subjects were mid-foot or fore-foot strikers, whereas at 5 m/s or less, most subjects were rear-foot strikers. Therefore, a change in running pace could drastically alter the force distribution throughout the foot. In their study, Keller et al. dealt with this by obtaining enough data to get a statistically valid number of samples at a range of different speeds. Many trials were done with the same runners running different paces so each pace could be compared individually. (Keller, et al., 1996; Munro, Miller, & Fuglevand, 1987)

Treadmill Running

Running on a treadmill has been viewed, for many years, as a substitute for outdoor running by many athletes. Treadmill running can be an adequate replacement for distance training, although it potentially creates changes in human gait that might alter some gait variables. A study conducted by Bristol showed significant differences ($p < .05$) in stride time, stride length, stance time, and swing time; all the tests for treadmill running and ground running were performed at equal speeds to ensure comparable results. Because any alterations in stride can lead to changes in both absolute maximum force and force distribution in the foot, testing subjects on a treadmill might not be an entirely reliable data source for reaching conclusions about ground running. (Bristol, 2001)

Another study conducted by Riley, et al. demonstrates that ground reaction forces are significantly lower on a treadmill than on ground. Although this study observed walkers, such a change in forces is likely to apply to running as well. (Riley, Paolini, Croce, Paylo, & Kerrigan, 2007)

Barefoot Running

In recent years, barefoot running has become increasingly popular because it provides runners with a less restricted and more natural feel. Although it might be more comfortable for runners in the short term, barefoot running often causes greater damage to the runner over time because of the lack of cushioning of the impact force. (Lieberman et al., 2010)

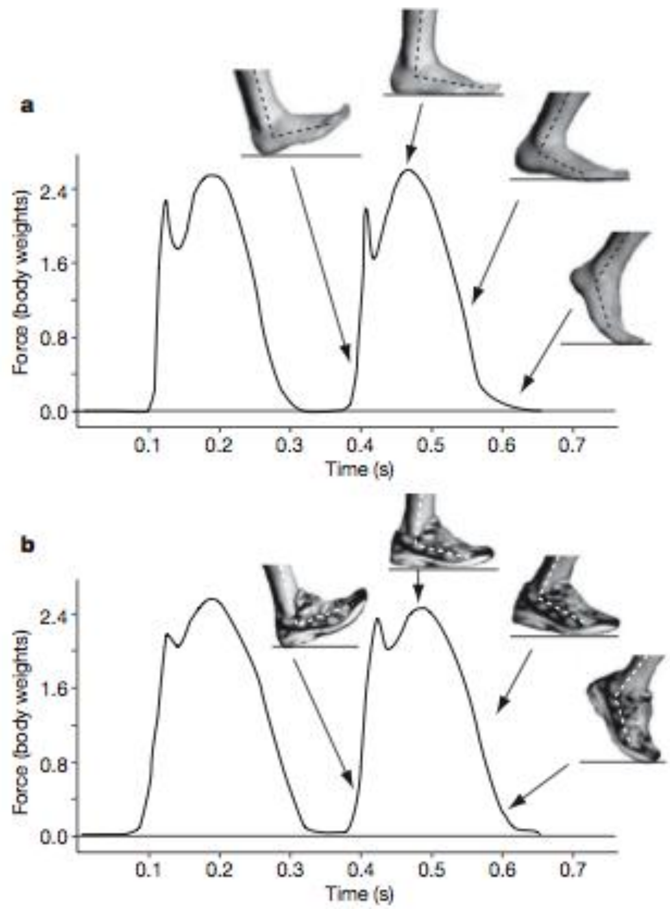


FIGURE 7: IMPACT FORCES BAREFOOT AND WITH SHOES

(LIEBERMAN, ET AL., 2010)

Methods of Measuring Spinal Rotation

There are several methods that have been used to measure spinal rotation. The most common method involves potentiometers to measure the changes in angle along the spine. The location of the potentiometers along the spine can vary; examples of this variation can be seen in their implementation in different spinal rotation measuring devices.

One device, the CA-6000 Spine Motion Analyzer, employs the use of six precision potentiometers to measure rotation, spinal flexion, lateral bending, and extension. Two studies conducted by Kumar utilize potentiometers to measure axial rotation. The devices used in these studies were not designed to be mobile, as is necessary for our application. The potentiometer devices can measure rotation from a seated human using a single potentiometer and a large harness. For measuring the spinal rotation of a runner, a smaller, more dynamic system would be necessary. (Kumar & Narayan, 1998; Kumar, Narayan, & Garand, 2003)

One method of measuring rotation is derived from a study examining the effectiveness of a technique to correct axial vertebral rotation in youths with Scoliosis was measured and "vertebral rotations were calculated relatively to the pelvis referential, so as a possible mispositioning of the patient in the system does not affect the results." This concept can be applied to measuring rotation in a runner in motion. (Obeid et al., 2009)

For a method using two potentiometers, one at the part of the spine where measurements are required and one at the pelvis or base of the spine as a reference point, the person being tested would not need to be seated or harnessed to obtain accurate results; the difference in angle between the two potentiometer readings would give the desired net spinal rotation. Potentiometers offer the advantage of being small, lightweight, and cost-effective, with a price of $5-20, depending on the degree of precision and tolerance needed for accurate results.

Another possible method of calculating spinal rotation involves using infrared LEDs and an array of cameras. This was shown as an effective method of calculating many gait measurements in a study by Bruijin, et al. In this study, clusters of LEDs were placed at strategic locations around the body. Cameras were then used to track the motion of each LED cluster. This could be useful in finding axial spinal rotation. This method allows a test subject to run relatively uninhibited because LEDs are extremely light; however, it is much more expensive and requires significantly more technology than other methods. (Bruijin, Meijer, Dieen, Kingma, & Lamoth, 2008)

Methods of Measuring Impact Forces in the Foot

The Model 13 sub-miniature load cells, made by Honeywell, potentially are usable for this application of measuring impact forces in the foot because of their small size (close to that of a penny), good accuracy (.7%), and high weight capacity (<1lb-1,000lbs). Unfortunately, this load cell is too costly (pricing at >$500 per load cell) for our project. (Honeywell, 2008)

Another method of measuring the impact force during running utilizes accelerometers which could be attached to the tops of each runner's shoes. With this method, the impact force could be determined by using a variation of the equation: force = mass * acceleration. This method would be substantially less expensive than other methods, but produces results so accurate that it provides more data than is usable in this project. (Digi-Key Corporation, 2010)

AccuSway force plates could be used by having the runners run directly over the plate. This method only works if the runner is able to contact the plate for every test without altering their gait. The limitation of using force plates for this application is that the impact forces of only one gait cycle are measurable at a time and one does not obtain results if the subject does not make contact with the force plate. The AMTI Netforce and Bioanalysis software which are used with the AccuSway allow for the impact forces and moments to be measured.

Measurement Systems

Multiple data-gathering devices were needed for testing. A force plate was utilized to measure three-dimensional impact forces and moments. A mechanical device was used to measure each subject's spinal rotation. Finally, a high-speed video camera was utilized to calculate runner speeds and limb accelerations. The specifications of all the equipment used in this experiment are detailed below.

The force plate used in our testing was the AccuSway^{Plus} by AMTI. It has a 600 lb vertical capacity and a 60 lb horizontal capacity. It is 0.5 meters long and wide. The plate is less than 2 inches tall and weighs 25 lbs. It is capable of gathering data at a rate of up to 50 Hz. It measures forces in the x, y, and z directions and moments about the x, y, and z axes. It also provides data on the center of pressure.

Spinal rotation was measured using a self-built mechanical device. It was constructed using an adjustable back brace, flat plastic sheets, and 1" diameter PVC pipes. The bottom section of the PVC is attached to the back brace. The top section of PVC is connected to the bottom by an elbow joint. The inside of the joint was sanded down to allow for rotation. The device is shown below (Figure 8). As the subject runs, the perpendicular section of pipe rotates to the maximum angle achieved. Friction prevents the pipe from rotating further than it is forced to. In order to measure the spinal rotation accurately, the device was removed after each trial. The displacement of the upper section from the neutral position (0^o of rotation) was measured. This displacement was then used to calculate the angle of rotation using the formula below. In preliminary tests of the device, the measurements were fairly repeatable. 10 trials were run with the same subject. The average angle was 13.54^o and the standard deviation was 2.6^o. The displacement was measured to the nearest thirty-second of an inch, which equates to 3.5^o, so the uncertainty in any measurements was 3.5^o.

$$\theta\ (radians) = \frac{s}{r}$$

$$s = displacement \qquad r = radius$$

FIGURE 8: SPINAL ROTATION DEVICE

The video camera used to record the trials was the Sony HDR-XR500V. It records in high definition, at 1920x1080 pixels. It features Smooth Slow mode, which records at 120 frames per second. This allowed for a precise analysis when calculating speeds and accelerations.

Methodology

Our project team conducted tests measuring the impact forces and spinal rotation that occurs while running, in order to analyze their correlation to overuse injuries. Our test group comprised of 20 male runners, ranging in age from 18 years to 22 year, height from 5’8” to 6’2”, and of average body weight for their height. All subjects had experience, prior or current, in competitive running. Prior to testing, each test subject was warned of the potential risks of this testing and then will be required to sign a waiver.

For each test subject, the testing included: 1) measuring the amount of spinal rotation of both the upper and lower back during running at a controlled pace, 2) recording impact forces in the feet using AccuSway^{Plus} force plates, and 3) a video analysis to determine the speed and acceleration of the test subject and their limbs.

Pre-test trials were conducted in order to determine each runner’s pace and stride length; this testing was done for the purpose of consistency through the actual testing. The subjects were instructed to land their right foot on the force plate every time for further consistency. The subject’s weight was recorded before trials with use of the force plate; and a photo of the subject was taken for sizing purposes. Also, the subject was required to fill out a survey about their past running and/or injury experiences.

During each test, subjects jogged approximately 50 meters at a comfortable pace of 6-8 miles/hour. The distance of approximately 50 meters allowed for the subject to have an approximate 30 meter buildup prior to reaching the force plates, and an additional 20 meters after contacting the force plates to return to walking. There were 6 trials done by each subject; three with running shoes, and three while barefoot. This was done in order to compare their natural gait while barefoot, to a gait that is possibly altered by the condition of the running shoe.

Spinal rotation was measured and recorded using our constructed spinal rotation device. The AccuSway^{Plus} force plate was used to measure impact forces that travel through the foot while running. The data that was averaged from the force plate is, stride length, F_z max, F_z avg, F_z impulse, F_y max, F_y min, F_x max, F_x min, and COM length. As well as this, F_z vs time and center of pressure graphs can be obtained.

Further, the project team used video analysis to measure how fast each subject ran and determine the presence (or absence) of any significantly noticeable abnormalities in the stride and speed of test subjects. In order to track the acceleration of each limb, the project team attached dots to each subject at the center of mass locations of their limbs. We used a high frame-rate camera from WPI Academic Technology Center (ATC) in combination with basic video editing software from Gordon Library to analyze the testing results.

To calculate the runners' speeds, the video from each trial was imported into Adobe Premiere Pro. Using this software, we were able to go through the footage, and export an image of each frame needed for analysis. From there, each image was imported into Adobe Photoshop. Using a known length from the video allowed us to calibrate all necessary measurements, converting pixels to feet. To calculate the runners' speeds, the distance from one point to another was needed. By overlaying the frames of interest, the distance between the markers could be measured. Once the distances had been found, they were put into an Excel spreadsheet. Runner speed was calculated by dividing the distance by the time elapsed.

The calculations for limb accelerations were initially done using two programs: Adobe AfterEffects and Microsoft Excel. First, video of a trial was imported into Adobe AfterAffects. Using the "track motion" feature, the distance in pixels in the x (forward) and y (vertical) directions of a marker from one frame to the same marker in the next frame was measured. This was done for a short period leading up to impact, the duration of the stance, and a short period after toe-off. These distances were input into Excel. Using a known distance from the video, the distances were calibrated and converted into feet. Dividing the distance covered by the frame length (1/120 seconds) gave limb speeds in both the x and y directions. Accelerations were then calculated by dividing the difference in speeds by frame length. This process was done for the upper leg, lower leg, and foot, resulting in vector speeds and accelerations for each. The equations are shown below.

$$v = \frac{\Delta d}{\Delta t} \qquad\qquad a = \frac{\Delta v}{\Delta t}$$

$$v = velocity \quad d = distance \quad t = time \quad a = acceleration$$

Graphing the speed and accelerations throughout the stance time showed that the data was sometimes noisy. This was likely due to imperfect measurement of pixel distance during the video analysis. With such a high-speed camera, the distance travelled in each frame was very small, so any error in measurement seemed large, even if it was only by a fraction of an inch. It became apparent that a smoothing function would be necessary to remove erroneous data and calculate more accurate speed and acceleration curves. Below is a sample scatter plot of lower leg speeds.

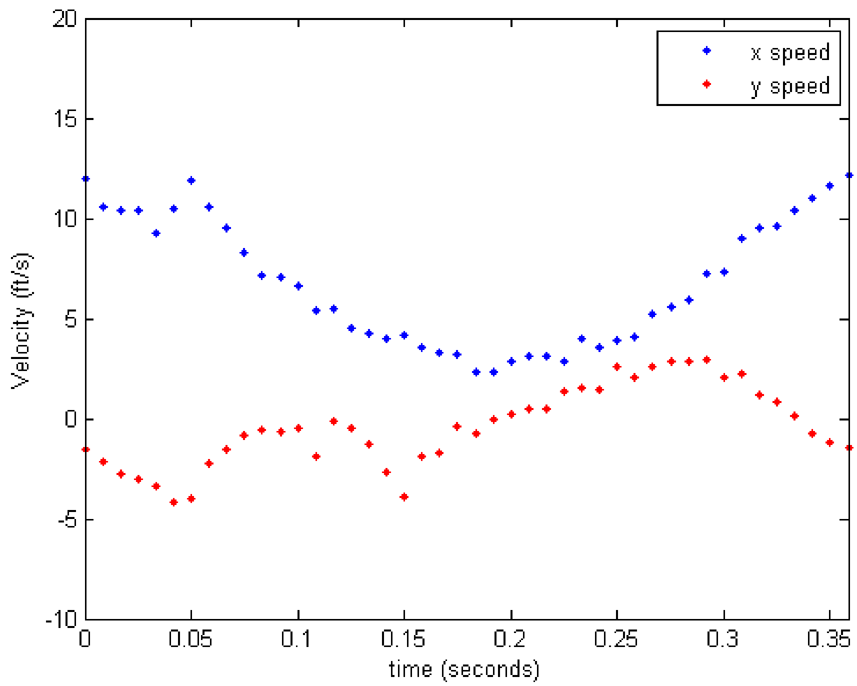


FIGURE 9: SAMPLE LOWER LEG SPEED PLOT

Matlab was used to filter our speed data. Using the curve fitting tool, we were able to import data from Excel and find a best fit polynomial for each set of velocities. Polynomials were chosen based on R^2 value. The graph below depicts the above scatter plot with curve fits.

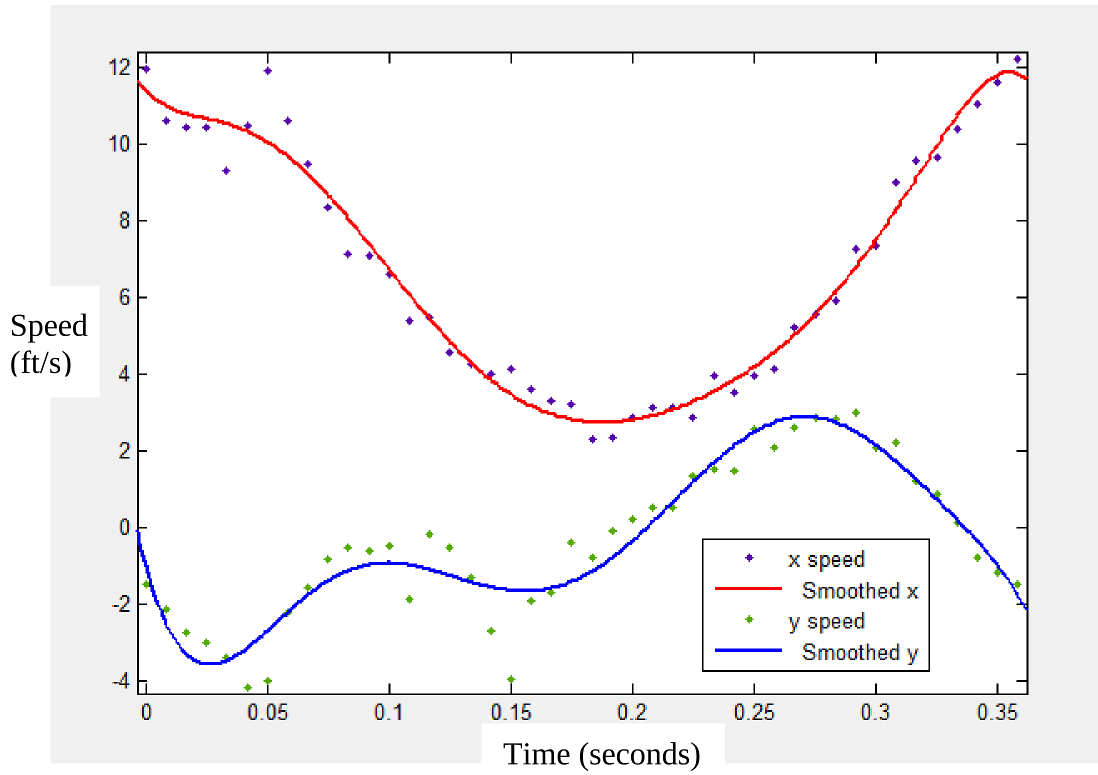


FIGURE 10: SAMPLE SMOOTHED LOWER LEG SPEEDS

Once the appropriate polynomial had been chosen for limb speeds in the x and y directions, the accelerations could be calculated. Using Matlab, the derivative of the polynomial was taken to produce an acceleration curve. This could be used to find the acceleration in the x and y directions for each limb at a given point in the stance time. All polynomials were chosen based on a 95% confidence interval. Two graphs of the acceleration curve for the above data are shown below.

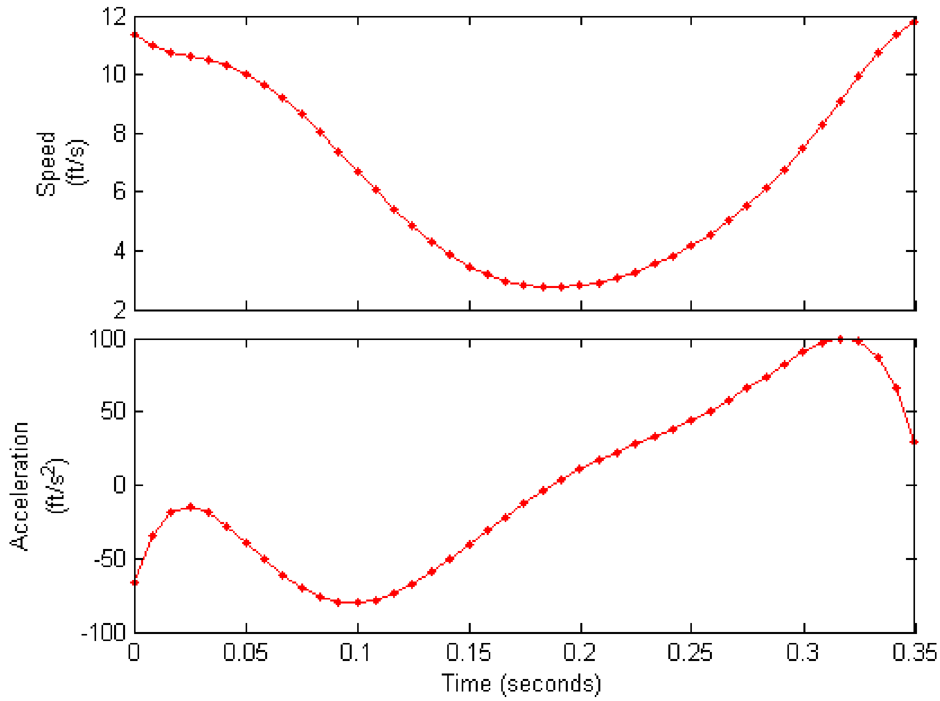


FIGURE 11: SAMPLE LOWER LEG SPEEDS VS ACCELERATION, X DIRECTION

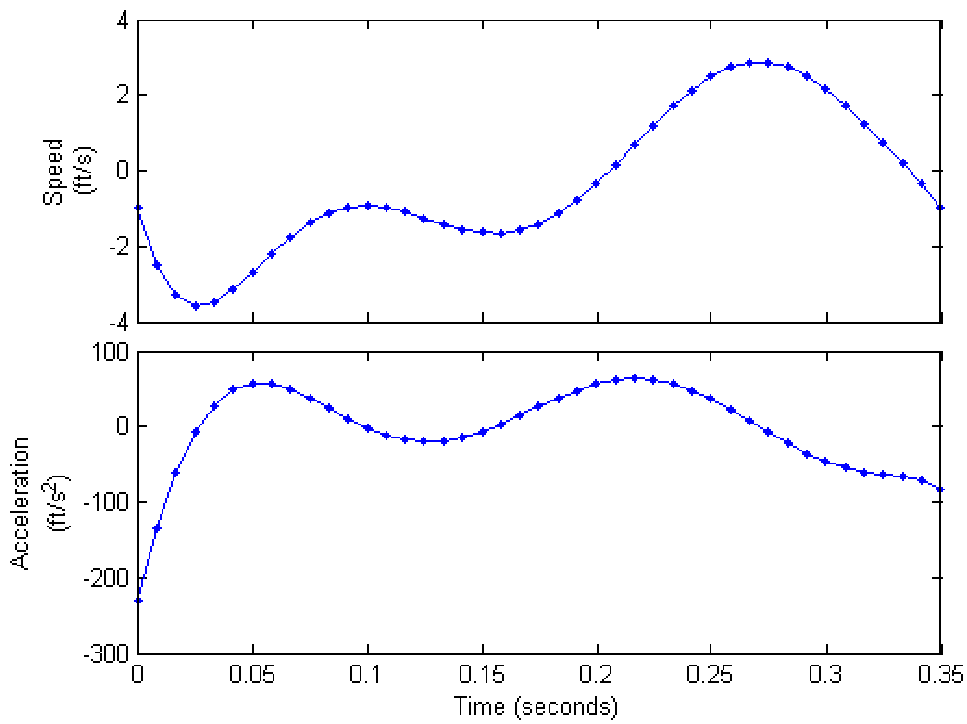


FIGURE 12: SAMPLE LOWER LEG SPEED VS ACCELERATION, Y DIRECTION

The resulting test data was used to determine how the pressure distributions in the foot correlate to the level of spinal rotation in an individual. The project team examined the results to determine the validity of the popular assumption that overuse injuries in running are directly related to abnormal pressure distributions in the foot, and to apply this to our hypothesis that spinal rotation is a factor.

Results

A large amount of data was gathered from the testing. The following tables summarize some of the key data obtained from the force plate, spinal rotation device, and video analysis. Table 2 depicts average spinal rotation, average normalized force (based on body weight and speed), and average speed for all trials of each runner. Table 3 shows the same variables for all trials with shoes. Finally, Table 4 contains the same variables for the trials that were conducted barefoot.

TABLE 2: ANGLE, FORCE, AND SPEED DATA FOR ALL TRIALS (SHOES AND BAREFOOT)

All Data (Shoes and Barefoot)			
Subject	**Avg. Angle (degrees)**	**Avg. Force (normalized for speed and weight)**	**Avg. Speed (mph)**
1	15.0	2.2	10.5
2	19.3	2.4	8.8
3	13.1	2.4	8.9
4	17.2	2.4	11.4
5	13.7	2.5	8.2
6	22.1	3.1	7.0
7	10.1	2.0	7.9
8	30.4	2.2	8.9
9	21.5	2.6	9.3
10	22.2	2.3	8.9
11	16.7	2.3	8.7
12	14.9	2.9	7.8
13	35.8	2.4	9.8
14	15.5	2.2	7.6
15	25.7	2.9	7.5
16	27.5	2.3	9.4
17	23.3	1.9	8.7
18	25.7	2.2	9.5
19	23.9	2.1	9.7
20	21.5	2.1	9.2

TABLE 3: ANGLE, FORCE, AND SPEED DATA FOR TRIALS WITH SHOES

Shoes Only			
Subject	**Avg. Angle (degrees)**	**Avg. Force (normalized for speed and weight)**	**Avg. Speed (mph)**
1	16.1	2.2	10.9
2	15.5	2.5	9.0
3	13.1	2.5	8.9
4	14.3	2.5	11.1
5	17.9	2.5	7.9
6	20.3	3.1	7.3
7	8.4	1.9	7.9
8	28.6	2.1	8.7
9	21.5	2.6	9.3
10	19.7	2.5	8.3
11	15.5	2.4	8.9
12	15.5	2.9	7.7
13	34.6	2.4	9.9
14	13.1	2.1	7.7
15	20.3	3.1	7.2
16	23.9	2.2	9.3
17	22.7	1.9	8.7
18	23.9	2.3	9.3
19	22.7	2.1	9.4
20	19.1	2.1	9.7

TABLE 4: ANGLE, FORCE, AND SPEED DATA FOR BAREFOOT TRIALS

Barefoot Only			
Subject	**Avg. Angle (degrees)**	**Avg. Force (normalized for speed and weight)**	**Avg. Speed (mph)**
1	14.3	2.3	10.1
2	25.1	2.4	8.5
3	13.1	2.2	8.9
4	21.5	2.3	11.7
5	9.5	2.6	8.4
6	23.9	3.1	6.7
7	11.9	2.1	7.8
8	32.2	2.3	9.0
9	21.5	2.6	9.2
10	23.9	2.1	9.6
11	17.9	2.3	8.5
12	14.3	2.9	7.9
13	37.0	2.4	9.8
14	17.9	2.3	7.6
15	31.0	2.6	7.8
16	31.0	2.4	9.5
17	23.9	1.8	8.7
18	27.5	2.1	9.7
19	25.1	2.1	10.0
20	23.9	2.1	8.7

Using the above data, we determined if there was any significant difference in speed, force, or angle between running with shoes and running barefoot. The statistical method of choice was the two-tailed, paired t-test. We did find a significant difference ($p = 0.0051$) between the angle of rotation for shod and barefoot runners. To investigate this further, a pairs comparison was conducted between shod and barefoot runners. The majority of the test subjects

(72.7%) exhibited larger angles of rotation while running barefoot; less than 20% of subjects (18.2%) yielded a greater angle while wearing shoes; and less than 10% of subjects (9.1%) showed comparable angles regardless of their footwear.

A t-test was also used to determine any difference in force between shod and barefoot runners. At a 95% confidence level, no significant difference was found (p=0.398). Similar results were found when calculating the probability of a difference in speed between the two groups, although no difference was expected. The p value for this comparison was 0.695.

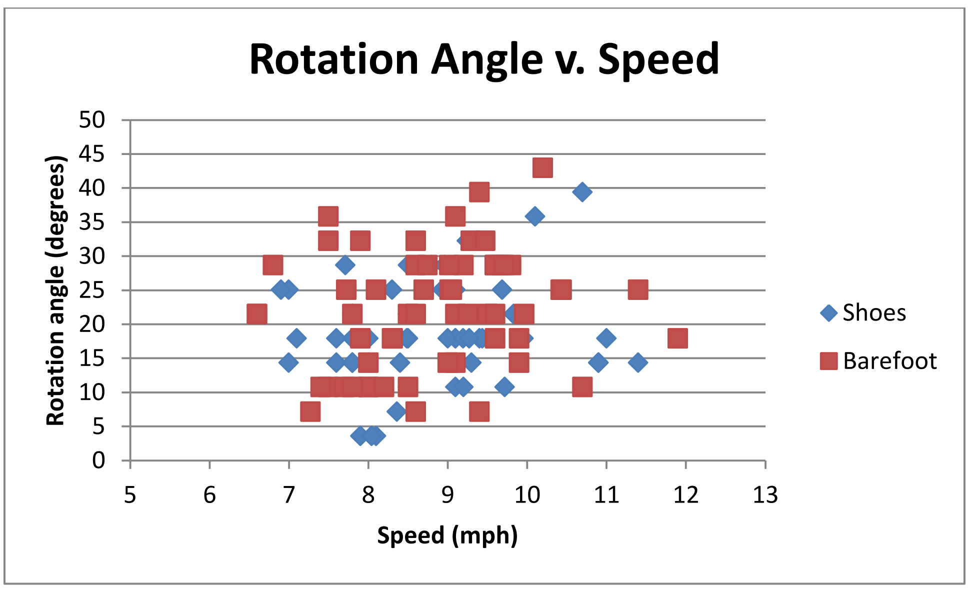


FIGURE 13: ANGLE OF ROTATION V. SPEED

Figure 13 relates rotation angle to the speed of the runner. This relationship was nearly identical with shoes and barefoot. A linear regression was conducted and the coefficient of determination (R^2) was calculated to determine if a statistical correlation existed. Both the shoes rotation angle v. speed and the barefoot rotation angle v. speed exhibited a very small R^2 value

(R^2=0.0418 and R^2=0.0359, respectively) showing that there is no statistical relationship between the angle of rotation and speed of the runner.

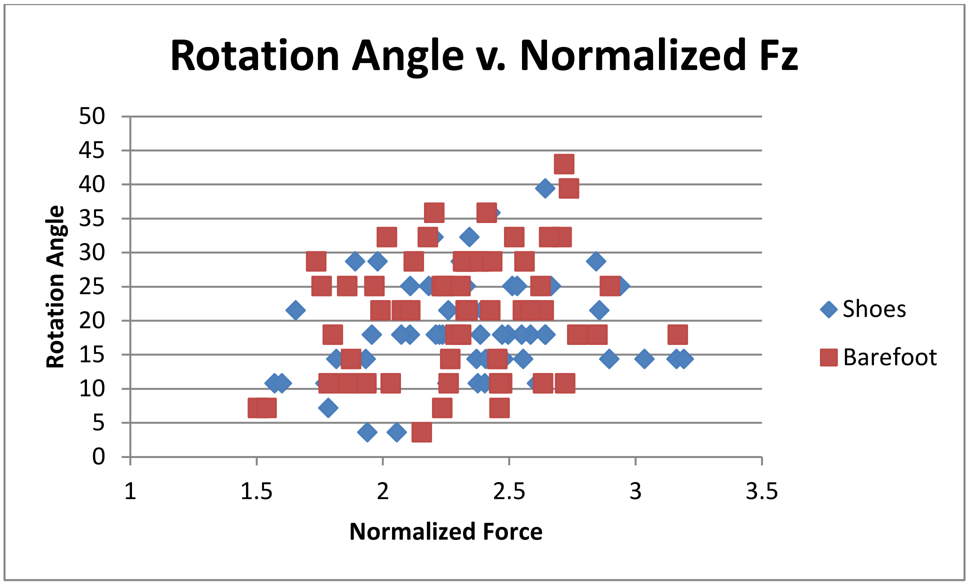


FIGURE 14: ANGLE OF ROTATION V. NORMALIZED VERTICAL FORCE

Figure 14 shows our comparison between the angle of rotation and the vertical forces. This relationship was nearly identical with shoes and barefoot. The R^2 values were very small (shoes: R^2=0.02777 and barefoot: R^2=0.0685) and proved no statistical relationship between the angle of rotation and the normalized vertical force.

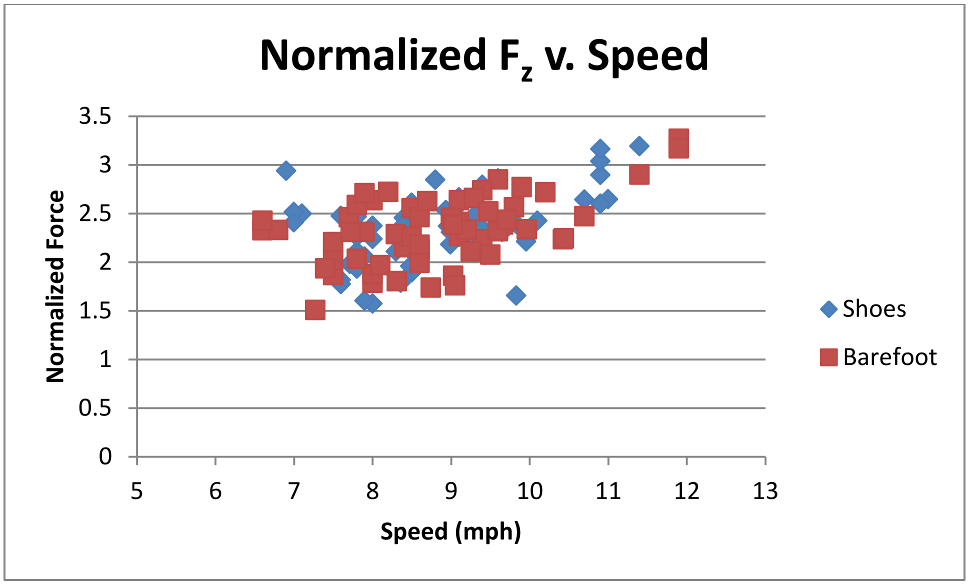


FIGURE 15: NORMALIZED VERTICAL FORCE V. SPEED

A comparison was conducted between the maximum vertical impact force and speed of the runner. Because the runners were of various body weights, the impact forces needed to be normalized to be able to compare the test subjects. The F_z forces were normalized by taking the maximum force in the vertical direction as a factor of the subjects' body weight. As with the rotation angle, minimal difference was seen between running with shoes and barefoot. The R^2 values were calculated (shoes: R^2=0.1867 and barefoot: R^2=0.2631). They showed that there is a mild statistical relationship between the normalized impact force and the speed of the runner.

Accelerations were also calculated for the limbs of the runners using Adobe AfterEffects, as discussed in the methodology. Acceleration data is available for the entire stance time, but we were only interested in the points of impact and toe-off. The table below shows acceleration values for a sample set of trials of 4 runners who ran at a range of speeds. All accelerations are in ft/s^2.

TABLE 5: SAMPLE OF ACCELERATION DATA

			Subject 1 (11 mph)	**Subject 2 (10 mph)**	**Subject 3 (9 mph)**	**Subject 4 (8 mph)**
Impact	**X direction**	upper leg acc	17.1	62.1	-38.9	-5.1
		lower leg acc	10.4	-35.6	-15.8	-14.4
		foot acc	-145.7	-172.7	-79.2	-109.2
	Y direction	upper leg acc	8.6	-44.4	-46.3	-3.9
		lower leg acc	8.6	89.6	84.3	-7.3
		foot acc	156.1	101.2	124.9	74.5
Toe-off	**X direction**	upper leg acc	-20.9	16.1	23.6	33.6
		lower leg acc	99.9	40.2	99.8	97.7
		foot acc	58.9	67.4	52.4	88.7
	Y direction	upper leg acc	-46.4	-53.2	-36.2	-86.8
		lower leg acc	-4.9	-65.0	-80.7	-62.4
		foot acc	126.5	75.8	104.4	30.1

For reference, speed and acceleration graphs for all limbs can be found in Appendix A.

To give an idea of the reliability of our testing methods, the table below shows the standard deviations for angle measurements. Our mechanical device is fairly simple, but the data shows that it does produce fairly repeatable measurements. Also, it must be considered that the subjects actually ran with different angles of rotation in each trial, which in Table 6 would give the appearance of unreliable data.

TABLE 6: STANDARD DEVIATIONS OF ANGLE MEASUREMENTS

Subject	**Average Angle (degrees)**	**Standard Deviation.**
1	15.0	3.0
2	19.3	6.0
3	13.1	4.3
4	17.2	4.7
5	13.7	5.3
6	22.1	4.2
7	10.1	3.5
8	30.4	3.8
9	21.5	3.2
10	22.2	3.9
11	16.7	3.7
12	14.9	4.2
13	35.8	6.0
14	15.5	8.4
15	25.7	7.7
16	27.5	8.4
17	23.3	4.9
18	25.7	4.2
19	23.9	3.7
20	21.5	3.2
Average:	20.8	4.8

Conclusions and Recommendations

From our analyses, we conclude that no correlation exists relating the speed of the runner to the normalized impact forces or angles of rotation. We also saw no relationship between rotation angles and impact forces, which was what we set out to test. From this conclusion, we would recommend testing a broader range of speeds to determine if there truly is no relationship or if no relationship was apparent simply because all the subjects ran at such similar speeds.

We also found a direct relationship between the footwear of the runner and the angle of rotation. The majority of subjects exhibited a larger angle of rotation while running barefoot. Ideally, further testing would be conducted to determine the cause of this relationship. We hypothesized that it could be because the subjects might not all have experience/be comfortable running barefoot. A subject base of inexperienced runners would help prove or disprove this relationship because they would not have such a developed gait. It would also prove useful to determine whether different types of shoes impact this relationship differently, or if it is that the runner is wearing shoes that cause it.

The use of a mechanical device, although it allowed the runners unrestricted mobility, could have caused errors in the angle data due to it being impossible to keep the friction within the device consistent. A potentiometer based device would allow for potentially greater consistency as well as the angle throughout the gait cycle, rather than just the maximum angle. Rotation angle could also be influenced and limited by the flexibility of the test subjects. To determine if this is the case, the maximum angle of possible rotation should be measured of all subjects before testing is conducted.

A mathematical model of the lower body's limbs could be used to further analyze the data gather during our project. Such a model would allow us to calculate the forces in the leg muscles as well as the resultant impact forces in the joints during heel strike and toe off of the gait cycle.

References

Auckland Bioengineering Institute. (2009). Muscle Activation During Gait. In YouTube (Ed.).

Baker, R. (2007). The History of Gait Analysis before the Advent of Modern Computers. *Gait & Posture, 26*(3), 331-342.

Ball State University. (2010). Ground Reaction Force. *Anatomical Kinesiology* Retrieved September 25, 2010, 2010, from http://www.bsu.edu/web/ykwon/pep294/lab8/grf_lab.html

Bertec. (2009). Force Plates Retrieved October 14, 2010, 2010, from http://bertec.com/products/force-plates.html

Bristol, A. (2001). A comparison of overground and treadmill running for measuring the three-dimensional kinematics of the lumbo-pelvic-hip complex. *Clinics in Biomechanics, 16*(8), 667-680.

Bruijin, S. M., Meijer, O. G., Dieen, J. H., Kingma, I., & Lamoth, C. (2008). Coordination of leg swing, thorax rotations, and pelvis rotations during gait: The orginisation of total body angular momentum. *Gait & Posture, 27*(3), 455-462.

Cavanagh, P. R. (1990). *Biomechanics of Distance Running*. Champaign, IL: Human Kinetics Books.

Digi-Key Corporation. (2010). Accelerometers Retrieved September 16, 2010, 2010, from http://search.digikey.com/scripts/DkSearch/dksus.dll?lang=en&site=US&WT.z_homepage_link=hp_go_button&KeyWords=accelerometers

Honeywell. (2008). Model 13: Subminiature Load Cell.

Keller, T. S., Weisberger, A. M., Ray, J. L., Hasan, S. S., Shiavi, R. G., & Spengler, D. M. (1996). Relationship Between Vertical Ground Reaction Force and Speed During Walking, Slow Jogging, and Running. *Clinical Biomechanics, 11*(5), 253-259.

Kumar, S., & Narayan, Y. (1998). EMG spectral characteristics of spinal muscles during isometric axial rotation. *Journal of Electromyography and Kinesiology, 91*(1), 21-37.

Kumar, S., Narayan, Y., & Garand, D. (2003). An Electromyographic study of isokinetic axial rotation in young adults. *The Spine Journal, 3*(1), 46-54.

Lieberman, D. E., Venkadesan, M., Werbel, W. A., Daoud, A., D'Andrea, S., Davis, I. S. D., . . . Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature, 463*(28), 531-536.

Munro, C. F., Miller, D. I., & Fuglevand, A. J. (1987). Ground Reaction Forces in Running: A Reexamination. *Journal of Biomechanics, 20*(2), 147-155.

Obeid, I., Aurouer, N., Hauger, O., Gille, O., Pointillart, V., & Vital, J. M. (2009). Axial Vertebral Rotation (AVR) Correction in All Screws Posterior Construct for Adolescent Idiopathic Scoliosis (AIS): Does Vertebral Column Manipulation (VCM) Help? *The Spine Journal, 9*(10), 110S-111S.

Perry, J. (1992). *Gait Analysis, Normal and Pathological Function*. New York, NY: McGraw-Hill.

Riley, P. O., Paolini, G., Croce, U. D., Paylo, K. W., & Kerrigan, D. C. (2007). A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. *Gait & Posture, 26*(1), 17-24.

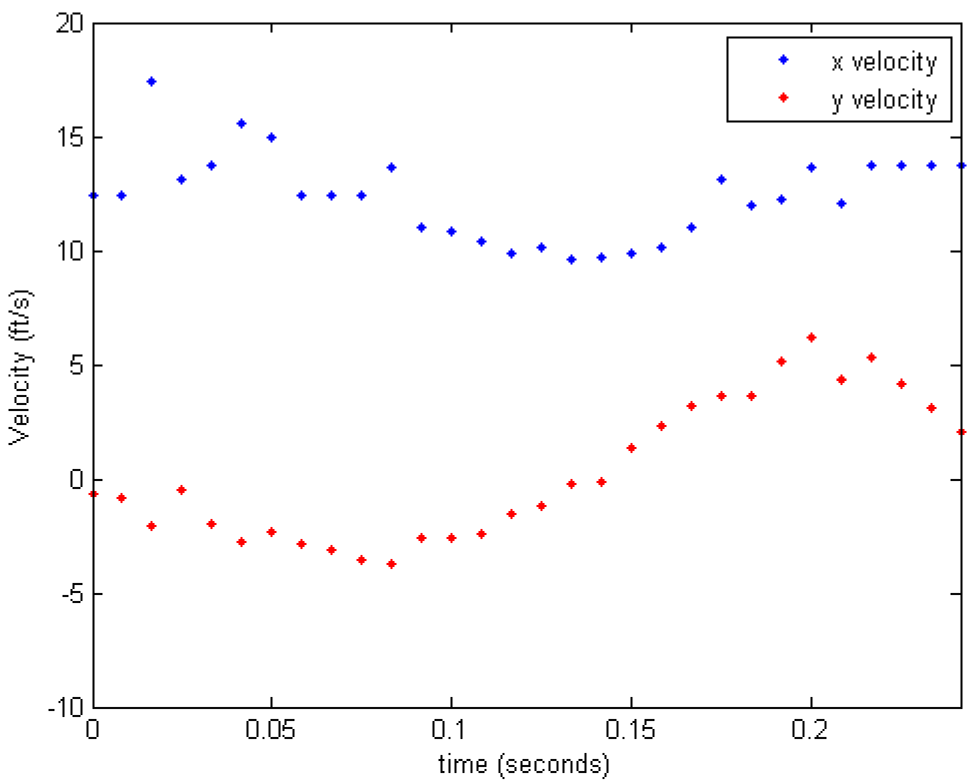
Tekscan. (2010). FlexiForce Load Force Sensors and Systems Retrieved September 16, 2010, 2010, from http://www.tekscan.com/flexiforce.html

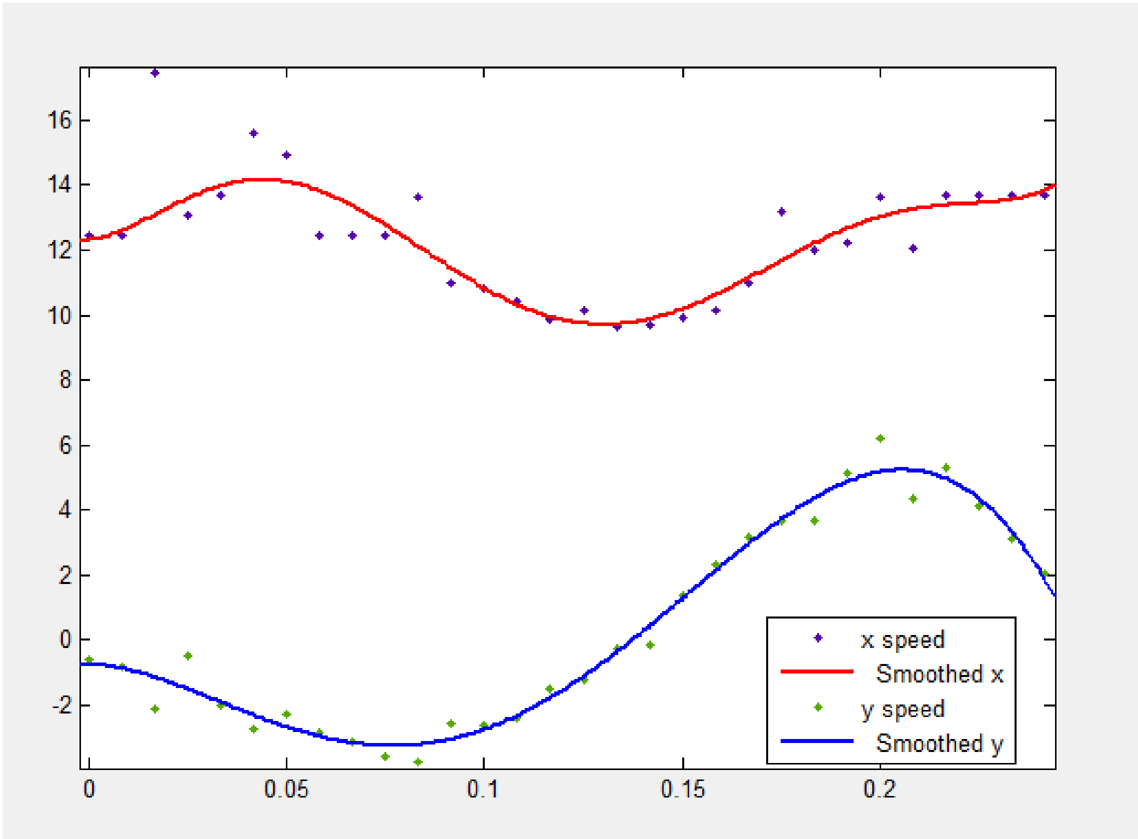
Wilder, R. P., & Sethi, S. (2004). Overuse injuries: tendinopathies, stress fractures, compartment syndrome, and shin splints. *Clinics in Sports Medicine, 23*, 55-81.

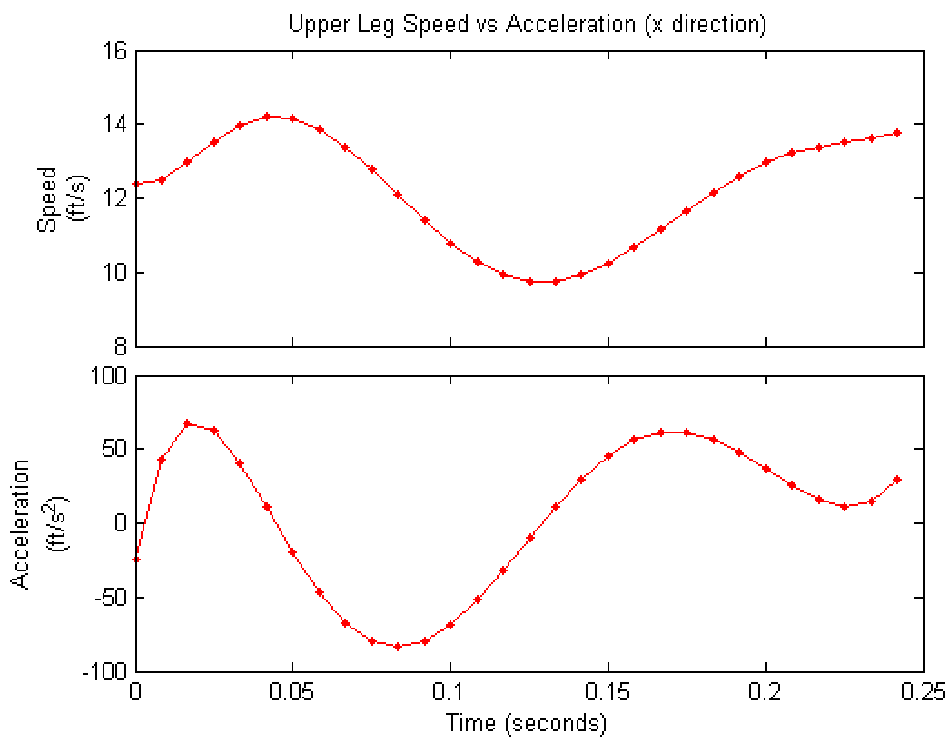
Appendix A: Acceleration Graphs

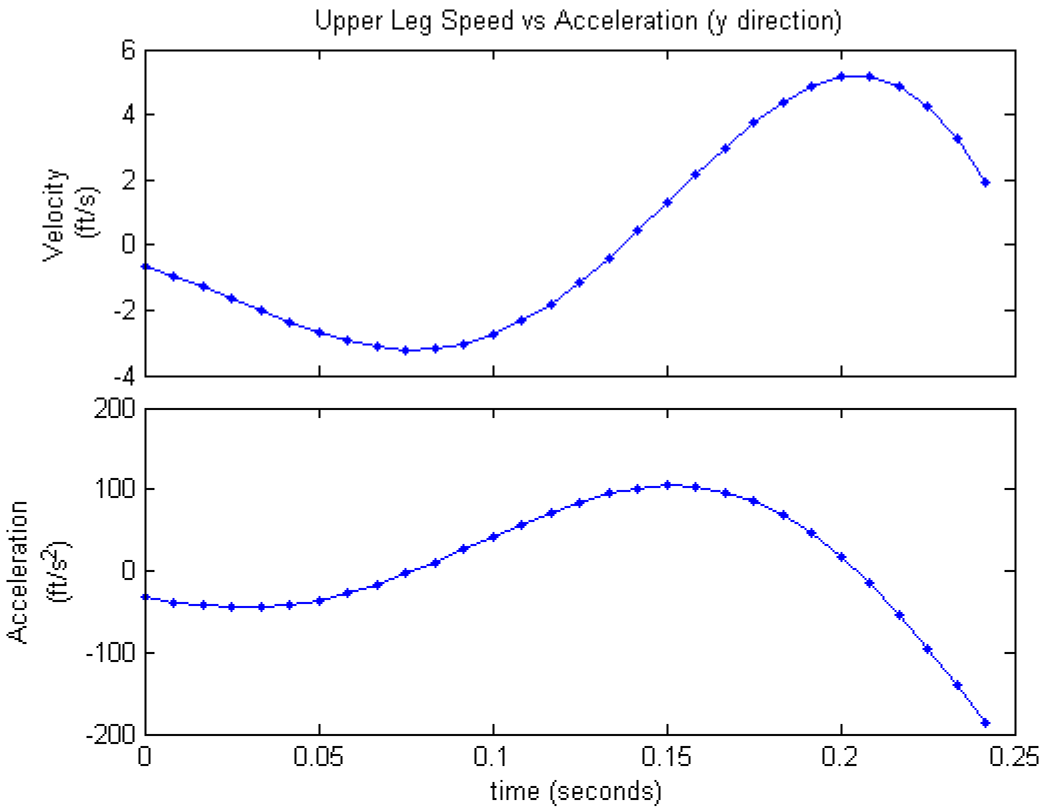
The following graphs depict a full analysis of a single trial of video. The analysis of each limb contains a plot of the original speed data, a plot of the curve fit for that speed data, a comparison of acceleration and speed in the x direction, and a comparison of acceleration and speed in the y direction.

Upper Leg Analysis

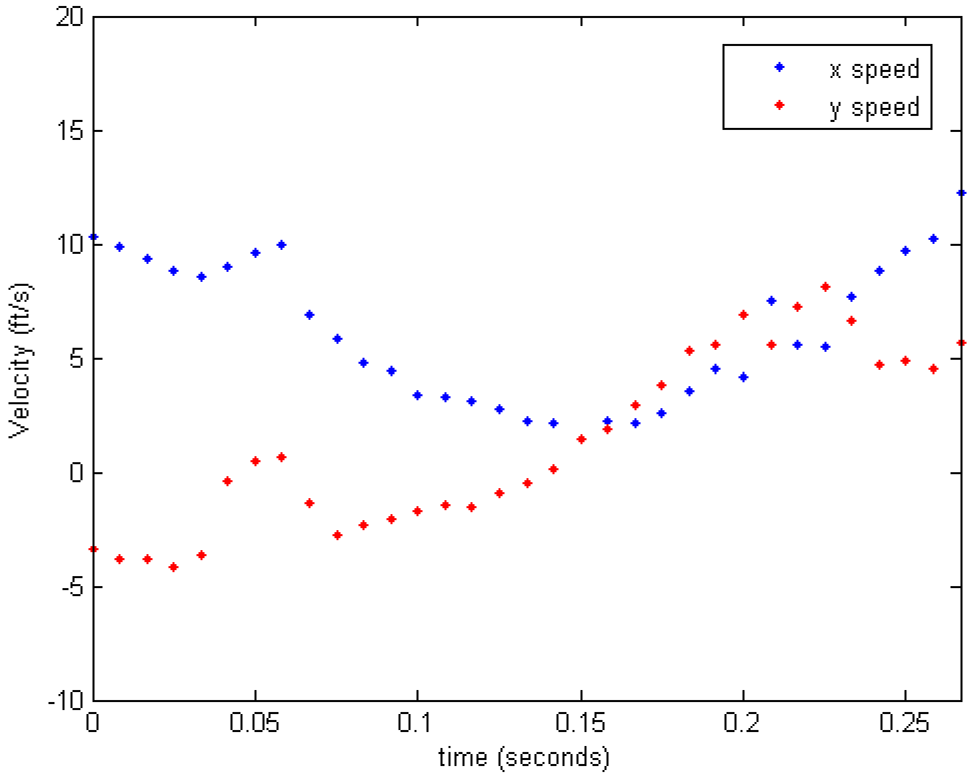


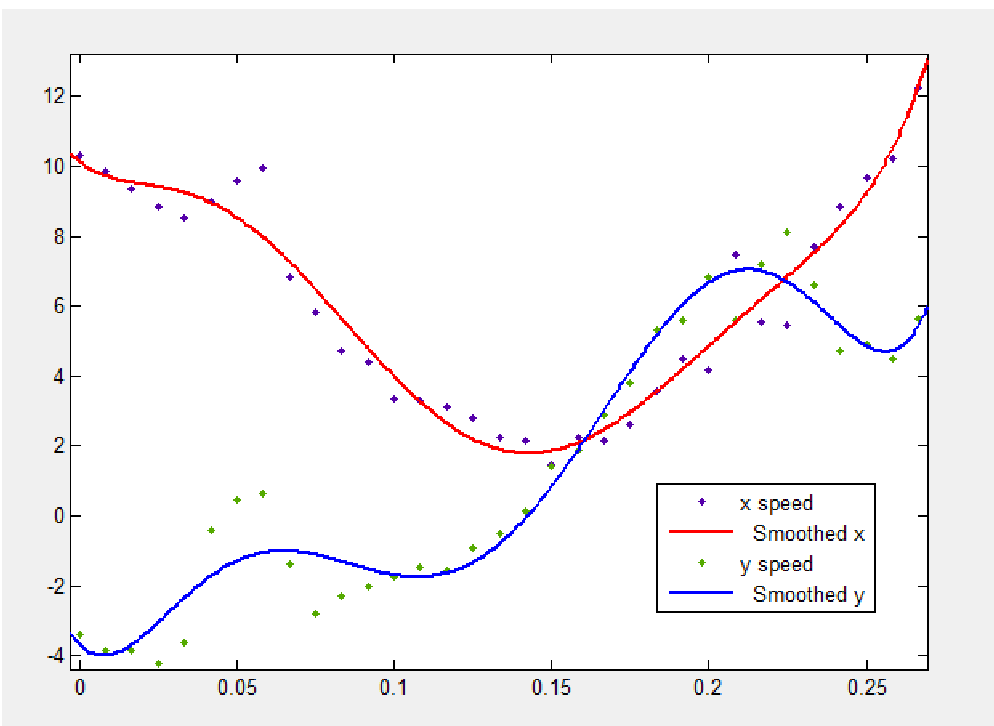

x speed
Smoothed x
y speed
Smoothed y

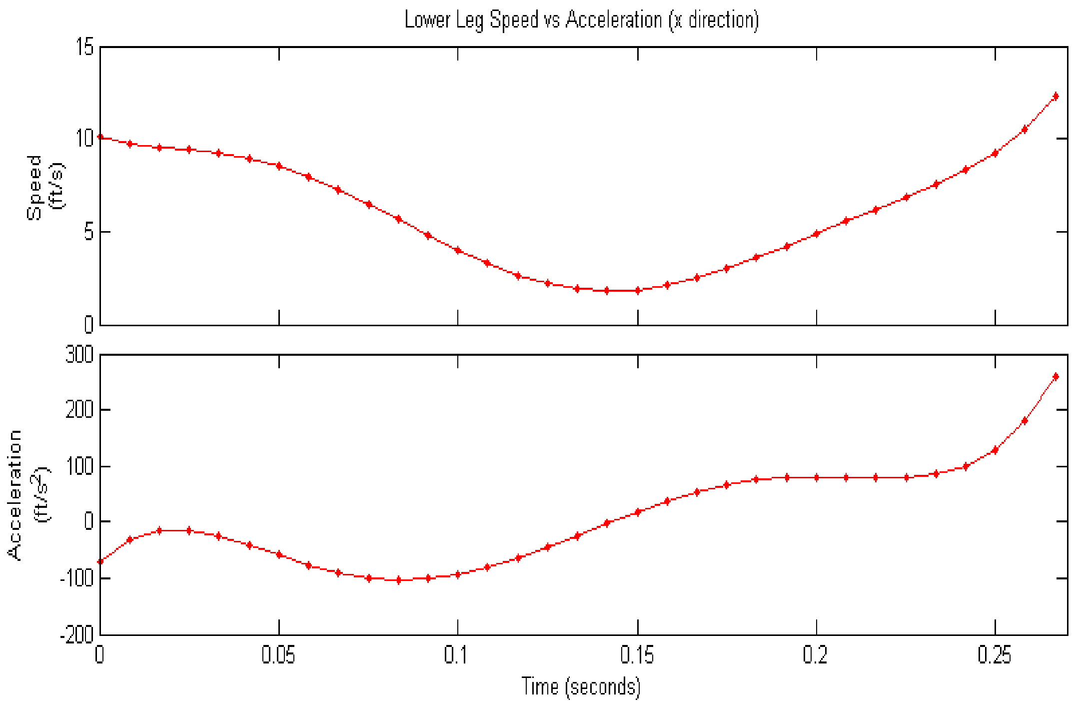

Upper Leg Speed vs Acceleration (x direction)
Speed
(ft/s)
Acceleration
(ft/s²)
Time (seconds)


Upper Leg Speed vs Acceleration (y direction)
Velocity
(ft/s)
Acceleration
(ft/s^2)
time (seconds)
6
4
2
0
-2
-4
200
100
0
-100
-200
0
0.05
0.1
0.15
0.2
0.25

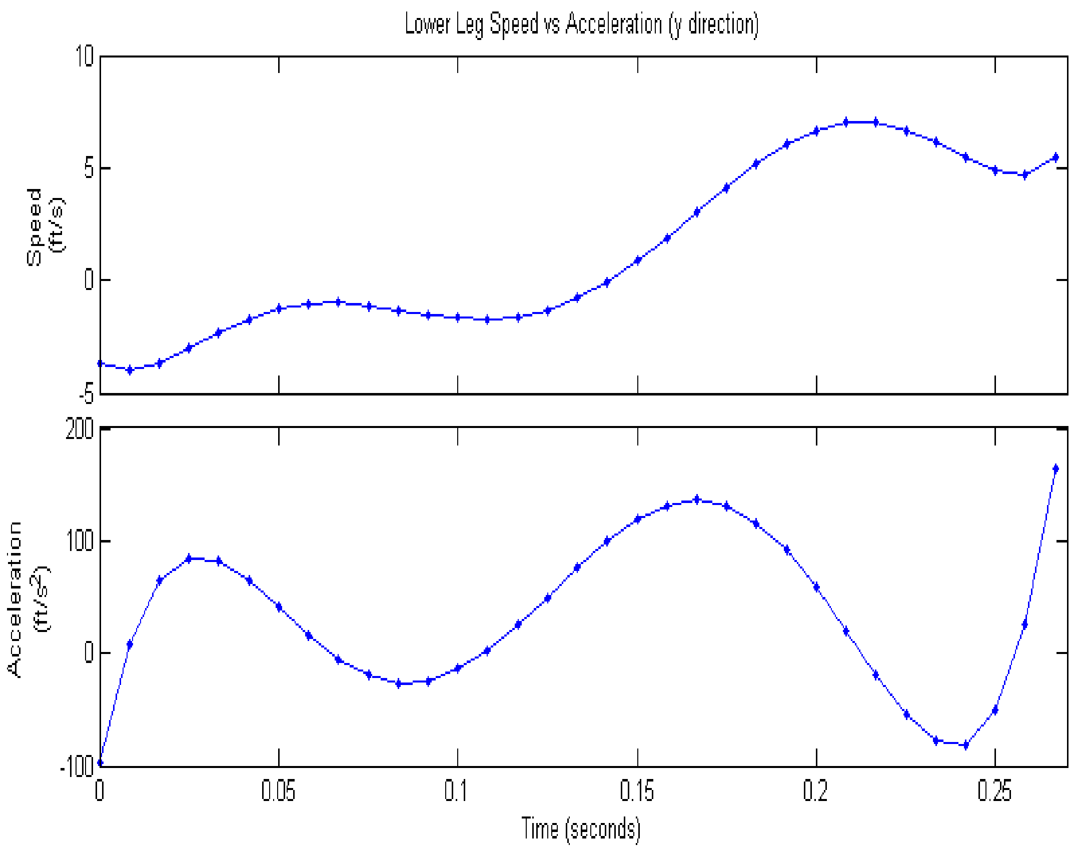
Lower Leg Analysis





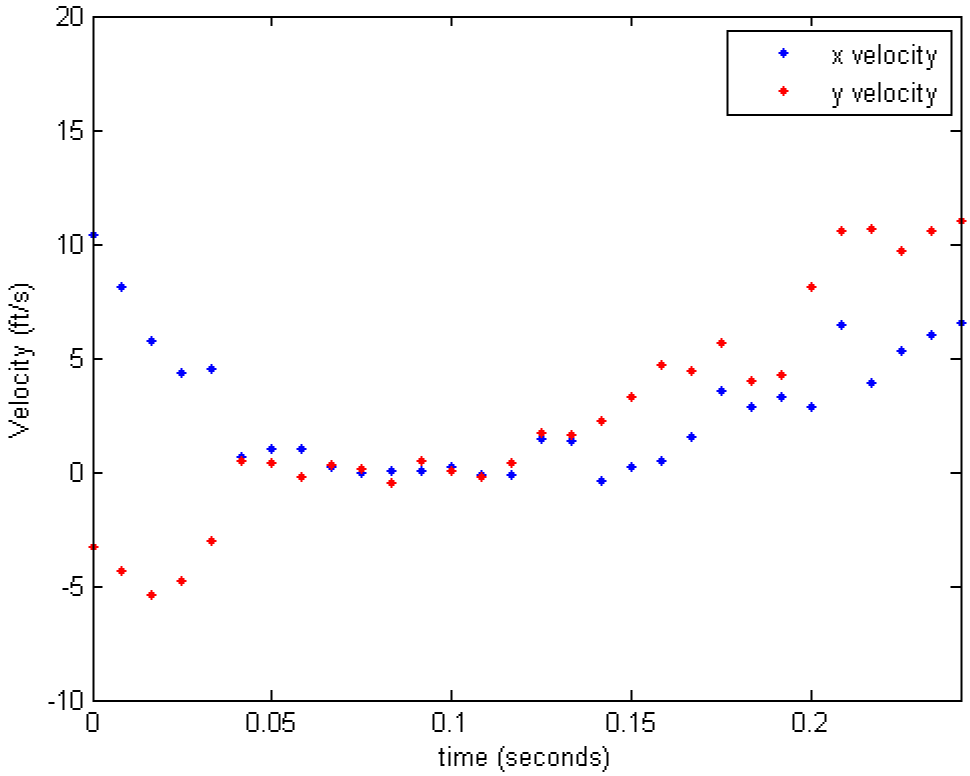


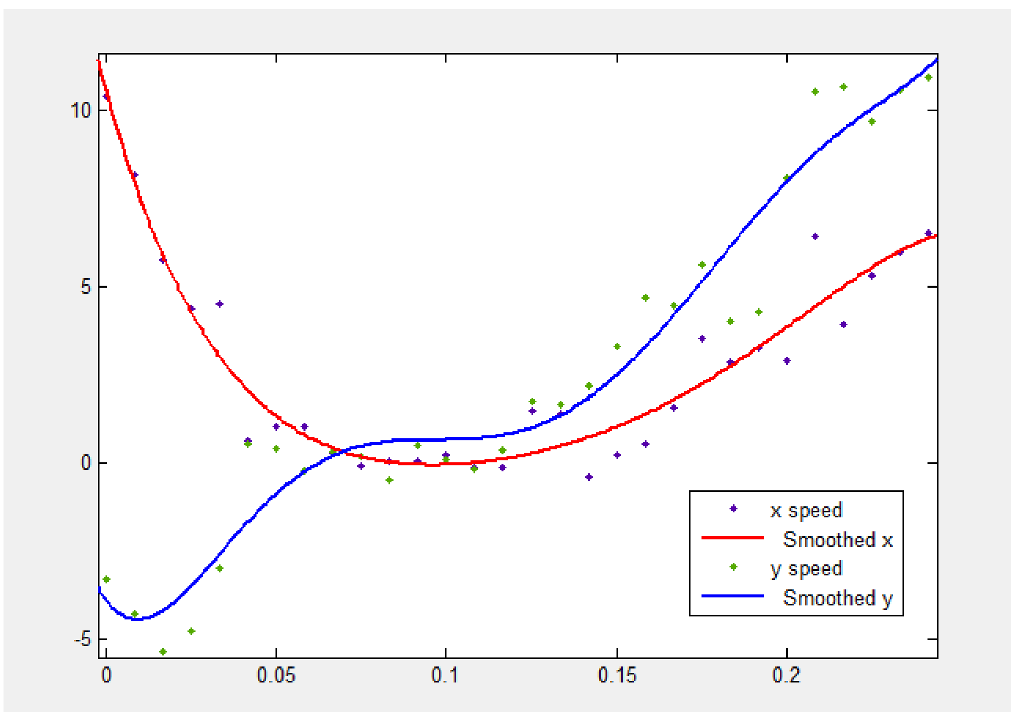
Lower Leg Speed vs Acceleration (x direction)
Speed (ft/s)
Acceleration (ft/s2)
Time (seconds)

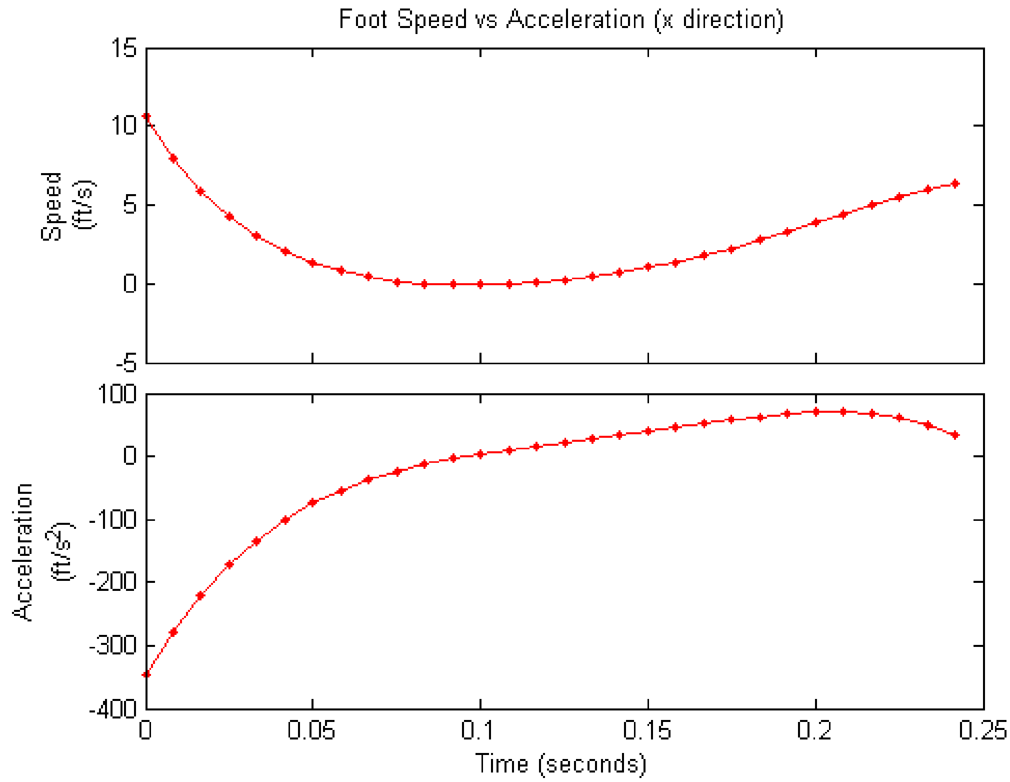


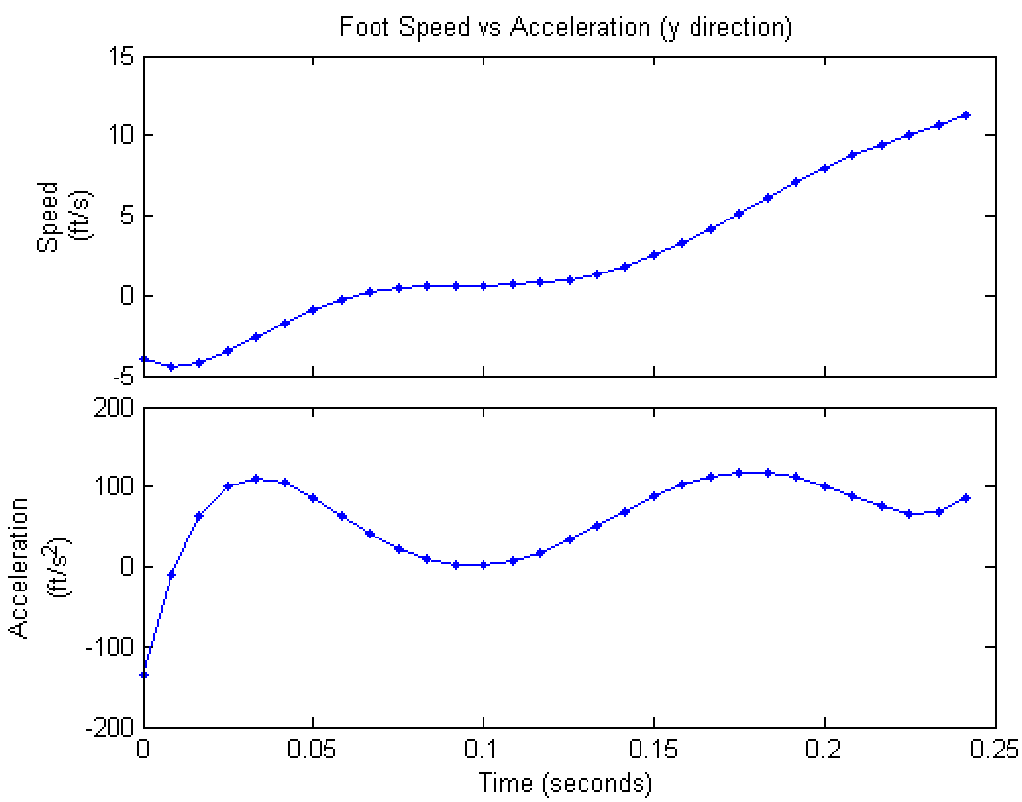
Lower Leg Speed vs Acceleration (y direction)
Speed (ft/s)
Acceleration (ft/s2)
Time (seconds)

Foot Analysis






Foot Speed vs Acceleration (x direction)
Speed
(ft/s)
15
10
5
0
-5
Acceleration
(ft/s^2)
100
0
-100
-200
-300
-400
0
0.05
0.1
0.15
0.2
0.25
Time (seconds)


Foot Speed vs Acceleration (y direction)
Speed
(ft/s)
15
10
5
0
-5
Acceleration
(ft/s^2)
200
100
0
-100
-200
0
0.05
0.1
0.15
0.2
0.25
Time (seconds)

Appendix B: IRB Approval

WPI

100 Institute Road
Worcester, MA 01609-2280, USA
508-831-5000, Fax: 508-831-6090
www.wpi.edu

Worcester Polytechnic Institute IRB #1
IRB 00007374

7 December 2010
File: 10-169

Worcester Polytechnic Institute
100 Institute Road
Worcester, MA 01609

Re: IRB Expedited Review Approval: #10-169 "Spinal Rotation during Running"

Dear Prof. Savilonis,

The WPI Institutional Review Committee (IRB) approves the above-referenced research activity, having conducted an expedited review according to the Code of Federal Regulations 46.

Consistent with CFR 46.116 regarding the general requirements for informed consent, we remind you to only use the **attached stamped approved consent form** and to give a copy of the signed consent form to your subjects. You are also required to store the signed consent forms in a secure location and retain them for a period of at least three years following the conclusion of your study. You may also convert the completed consent forms into electronic documents (.pdf format) and forward them to the IRB Secretary for electronic storage.

The period covered by this approval is 7 December 2010 until 6 December 2011, unless terminated sooner (in writing) by yourself or the WPI IRB. Amendments or changes to the research that might alter this specific approval must be submitted to the WPI IRB for review and may require a full IRB application in order for the research to continue.

Please contact the undersigned if you have any questions about the terms of this approval.

Sincerely,

Kent Rissmiller

Kent Rissmiller
WPI IRB Chair

Appendix C: Consent Form

Informed Consent Agreement for Participation in a Research Study

Investigator: Alex Browning, Deanna Flaherty, and Joe Worthen

Contact Information: mqp-sr10@wpi.edu

Title of Research Study: Spinal Rotation while Running

Purpose of the study: Tests are being conducted measuring the impact forces and spinal rotation to analyze their correlation and relation to injuries.

Procedures to be followed: During each test, subjects will jog approximately 50 meters at a comfortable pace. The distance of approximately 50 meters will allow for the subject to have a ~30 meter buildup prior to reaching the force plates, and an additional ~20 meters, after contacting the force plates to return to walking. Pre-testing will be conducted to determine each runner's pace and stride length; this testing will be done for the purpose of consistency through the actual testing. The locations of the force plates will be determined based on each subject's stride length. Pre-test trials will be conducted in order to place the force plates for the subject to contact the force plates without changing their stride or pace. Each subject will participate in 10 recorded trials. In each test we will measure the speed, impact forces, and spinal rotation of the subject. From the impact forces we will examine the distributed forces throughout the feet.

We will be measuring the spinal rotation using a potentiometer device. The potentiometer has been designed to allow for measurements to be recorded on the patient, allowing for portability, rather than being hard wired.

We will also be using video analysis to measure how fast each subject runs and to determine the presence (or absence) of any significantly noticeable abnormalities in the stride and speed of test subjects. To track the acceleration of each limb, we will attach dots to each subject at the center of mass locations of their limbs.

Risks to study participants: Normal discomfort induced by running

Benefits to research participants and others: An explanation of how spinal rotation affects impact forces in the body while running and how that also affects the likelihood of injuries occurring

Record keeping and confidentiality: All recorded data from these tests will be maintained by the members of the MQP group until the conclusion of the project. At the conclusion of the project, all data will be transferred to Professor Savilonis. No data allowing for personal identification of the subjects will be required.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact: Alex Browning, Deanna Flaherty, or Joe Worthen at mqp-sr10@wpi.edu.

If additional assistance is required, please contact IRB Chair (Professor Kent Rissmiller, Tel. 508-831-5019, Email: kjr@wpi.edu) and the University Compliance Officer (Michael J. Curley, Tel. 508-831-6919, Email: mjcurley@wpi.edu).

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

____________________________ Date: ____________________

Study Participant Signature

____

Study Participant Name (Please print)

_____________________________________ Date: ____________________

Signature of Person who explained this study